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SURVEY OF VULNERABILITY METHODOLOGICAL NEEDS

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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13. ABSTRACT (*Maximum 200 words*)

Several different models are currently in use for the analysis of the vulnerability of armored fighting vehicle (AFV) to direct fire weapons. However, recent reports have declared that the suite of models is insufficient, especially in the low detail, quick turn-around regime.

In the task described in this report, dozens of users were interviewed. Spanning the field of applications from AFV and warhead design to theater-level modeling, these users reported their perceptions of the state of vulnerability modeling. These perceptions, without rebuttal, are faithfully reported here. Significantly, no need was voiced for a new model.

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I. Introduction

A. Hierarchy of Models

Several different models are currently in use for the (item-level) analysis of the vulnerability of armored fighting vehicles (AFV) to direct fire weapons. As shown by Deitz [1], these models can be categorized into five classes:

- Penetration Models
- Lumped Parameter (Compartment) Models
- Expected-Value Point Burst Models
- Spare Parts Models
- Stochastic Point Burst Models

Table 1, taken from Deitz (*op cit.*), lists a number of those models and their salient features.

However, in its 1989 report[2] on the adequacy of vulnerability analysis, the Board on Army Science and Technology (BAST) declared that the above hierarchy was both incomplete and mis-directed. In particular, the BAST indicated that effort in the development of detailed models was wasted. Rather, they maintained, what was needed was another level of modeling, lying between Penetration and Lumped Parameter Models, which would presumably produce results of an accuracy and in a production time intermediate to those of the existing models.

It is the purpose of the present study to verify the need for such a model and, if the results warrant, determine the characteristics (required accuracy, allowable time for a study, etc.) that such a model must possess in order to fill the established need.

[1] Dr. Paul H. Deitz, Presentation to the Blue Ribbon Panel on Vulnerability Methodologies, USABRL, 1990

[2] *Armored Combat Vehicle Vulnerability to Anti-armor weapons: A Review of the Army's Assessment Methodology,* Committee on a Review of Army Vulnerability Assessment Methods, Board on Army Science and Technology, **Commission on Engineering and Technical Systems, National Research Council,** National Academy Press, Washington, D.C., 1989

Table 1: Direct-Fire AFV Models

<table>
<tr><th>METHODOLOGY</th><th>MODEL APPLICATIONS</th><th>STRENGTHS/WEAKNESSES</th><th>PLANNED IMPROVEMENTS</th></tr>
<tr><td>Penetration Performance</td><td>• Armor (BH&T) Design
• Warhead/Pen Design</td><td>+/- Good or Bad as TBD formulae
+ Overmatch Metric</td><td>• Closer Ties to TBD (Done)
• Merged under MUVES (Done)</td></tr>
<tr><td>Lumped Parameter
Compartment Code/ VAMP</td><td>• Production V/L Support
• Concept Vehicle Design
• Lethality Enhancement
• Compartment-Level Studies</td><td>+ Minimal Geometry
+ No Spall/PK|H Data Req
+ Fast Run Times
+ Incls Secondary Kill Mechanisms
- Applicable only to Tested Systems</td><td>• Merged under MUVES (Done)
• Sensitivity Analyses
• Derivative Correlation Curves</td></tr>
<tr><td>Expected-Value Point Burst
SLAVE</td><td>• Lethality Enhancement
• Vulnerability Reduction
• Component-Level Studies</td><td>+ One-Cone Spall Model
+ Simple PK|Hs
- Detailed Geometry
- Fault-Tree Analysis
- Damage Mechanisms Explicit</td><td>• Future MUVES Merger</td></tr>
<tr><td>SIMVA</td><td>• Lethality Enhancement
• Vulnerability Reduction
• Component-Level Studies</td><td>+ 3-Cone Spall Model
+ Simple PK|Hs
- Detailed Geometry
- Fault-Tree Analysis
- Damage Mechanisms Explicit</td><td>• Future MUVES Merger</td></tr>
<tr><td>STEVE</td><td>• Lethality Enhancement
• Vulnerability Reduction
• Component-Level Studies</td><td>+ Continuum Spall
+ Simple PK|Hs
- Detailed Geometry
- Fault-Tree Analysis
- Damage Mechanisms Explicit</td><td>• Future MUVES Merger</td></tr>
<tr><td>VAST</td><td>• Lethality Enhancement
• Vulnerability Reduction
• Component-Level Studies</td><td>- M/V/S Spall Model
- M/V/S PK|Hs
- Detailed Geometry
- Fault-Tree Analysis
- Damage Mechanisms Explicit</td><td>• Future MUVES Merger</td></tr>
</table>

Table 1: Direct-Fire AFV Models

METHODOLOGY	MODEL APPLICATIONS	STRENGTHS/WEAKNESSES	PLANNED IMPROVEMENTS
Spare Parts			
VAST +	• Estimate of Damaged Parts • Estimate of Repair Times	- M/V/S Spall - M/V/S PK|Hs - Detailed Geometry - Fault-Tree Analysis - Damage Mechanisms Explicit	• Future MUVES Merger
SQuASH +	• Estimate of Damaged Parts • Estimate of Repair Times	+ Full Stochastic Accounting + Explicit Damage Vectors + Simple PK|Hs - Detailed Geometry - Fault-Tree Analysis - Damage Mechanisms Explicit	• Future MUVES Merger • Secondary Kill Mechanisms
Stochastic Point Burst			
SQuASH	• Live-Fire Predictions • Lumped-Parameter Calibration • Vulnerability Reduction • Lethality Enhancement • Component-Level Studies • Research Tool • Stochastic LF Penetration	+ Full Stochastic Accounting + Explicit Damage Vectors + Simple PK|Hs + Moderate Spall + Degraded States Option - Damage Mechanisms Explicit - Detailed Geometry - Fault-Tree Analysis	• Future MUVES Merger (Oct 92) • Secondary Kill Mechanisms

B. Approach

Although the BAST specifically indicated the Equipment-Design Community as the beneficiaries of the new model, it was decided to canvass the greater community of vulnerability data users to determine where the unfulfilled needs actually lie. The approach, therefore, was to assemble a list of uses and users through discussions with various members of the Vulnerability/Lethality Division of the Ballistic Research Laboratory. Interviews were then conducted with individuals representing each level of use. Finally, the findings from these interviews were collated into similar needs and solutions to fill those needs were proposed.

> It must be noted, therefore, that **all comments and opinions in the section entitled "Surveys" are those of the interviewees,** as faithfully reproduced as memory and understanding serve the author. The "Summary and Recommendations" section contains a synopsis of these comments, along with a prima facie evaluation by the author.
>
> It is important to note that this document purposely contains no evaluation of the comments and opinions, nor rebuttal of any criticisms, by those in the BRL who are responsible for the development of the methodologies which form the subject of the interviews. In particular, on-going projects which address some of the identified shortfalls are not described in this document. Rather, it was decided to confine this document to the currently held viewpoints of the *users*, allowing the *developers* publish a companion document in response.

II. Users

A table of uses and users of direct-fire, AFV vulnerability data is presented in Table 2.

Note that, in a very loose, qualitative sense, the uses are arranged, in increasing order, by the scope of the studies in which the vulnerability data is used. Conversely, the order tends to reflect a decreasing level of required detail. (Exceptions abound. For example, it has been pointed out that warhead design, although involving small scope and presumably high detail, is aimed at futuristic (non-existent) threats for which little detail can be specified for the target. However, warhead design analyses tend to remain one-on-one, with certain selected factors (e.g. armor configuration) hypothesized with significant detail.)

The credentials of the specific interviewees were established as follows. In all cases, the author "entered the organization" by explaining the purpose and scope of the study to a relatively highly placed individual in the organization to be interviewed. The actual interviewees were specifically designated by these individuals. It can therefore be inferred that the responses received were from knowledgeable sources.

A. Interview Questions

It was anticipated that the responses from the various users would reflect the wide variation that exists in the user community. However, it was also hoped that common requirements would emerge, and that these could be grouped into sets that could be satisfied by the various available models. The existence of an unsatisfied set would therefore constitute a verified need for a new model.

In order to group the user needs, it was necessary to standardize the responses. An attempt was made to standardize the questions to be asked of respondents: The goal was to identify those salient characteristics that are truly required of a vulnerability/lethality methodology to meet the user's needs without unduly burdening or delaying his established operating procedures. The ideal response, therefore, would be a typical time-line for a typical product of an agency.

However, it was also desired to encourage the interviewees to speak freely. The author was particularly wary of influencing the responses by his phrasing of questions. Moreover, several of those interviewed preferred to enumerate

Table 2: Uses and Users of AFV Vulnerability Data

USES-USERS

BALLISTIC RESEARCH LABORATORY

US ARMY
LABORATORY COMMAND

Total Scope of Study ↓

Required Detail in Vulnerability Analysis ↑

Use		User
• Equipment Design		TACOM, PMs
• Warhead Design		MICOM, ARDEC, PMs
• Test Prediction/Postdiction		BRL, AMSAA, TECOM
• Item-Level Performance		AMSAA, PMs, JTCG/JMEM
• SPARC		AMSAA
• Operational Planning		TRADOC
• Force Level Models	High Res.	TRAC-WSMR, AMSAA
	Medium Res.	TRAC-FLVN
	Low Res.	CAA
• COEA,SSEB, Ad hoc Studies		TRAC for TRADOC

wants and dislikes directly. Therefore, the attempt to make a standardized list of questions to be asked of the respondents was abandoned: *no such list was made.* Rather, the author adopted the following interview procedure:

A. Describe the interviewer's motivation; viz: to determine the sufficiency of the suite of BRL vulnerability models.

B. Encourage the interviewee to speak freely on his uses, problems, likes and dislikes with BRL vulnerability models/data.

C. If the interviewee strays too far from the above topic, bring him back to the subject with very general questions such as:

   - Can we construct a time-line for a typical study/operation/etc.?
   - How accurate are the results of your studies? How is that accuracy affected by the accuracy of the vulnerability data?
   - How much expertise does your organization possess in the areas of vulnerability analysis?
   - What other limitations do you have on your operation?
   - To which agencies do you go for vulnerability methodologies or data?

   In addition, several interviewees had comments which they felt were important to express; some even had pre-listed such comments in anticipation of the interview. If germane in the broad scope of this report, these comments are included in the appropriate sections.

   The conclusions to be drawn from this description of the procedure are as follows:

   - The responses of the interviewees were not led by the interviewer except toward the broad area of vulnerability methodology needs.
   - Interviewees were encouraged to quantify their responses, if possible.
   - Finally, interviewees were made cognizant of the broad interests of the interviewer and were thus aware that any needs in the area of vulnerability analysis were appropriate. Thus, it can be concluded that the absence of an issue/complaint is significant.

III. Surveys

A. Equipment Design

In the area of equipment design, several offices/POCs were contacted. These are listed in Table 3.

Table 3: Equipment design offices and POCs contacted

TACOM: RD&E Center	COL Kanda, Dr. Beck
TACOM: Armor Division	Mr. Sam Goodman
PM-Bradley	MAJ Burton
PM-Survivability Systems	Dr. Terrence Dean
PM-AFAS	Mr. T. Kuriata
PM-AMMOLOG	Mr. Juris Miemis
PM-FARV	COL Voss, Dr. Goble
General Dynamics Land Systems	Dr. Gary Jackman
General Motors Military Vehicles	Drs. John Waller, John MacBain

1. RD&E Center

Figure 1 shows a typical timeline for the development of a tank concept, based upon discussions held at TACOM. For comparison, a process flow-chart taken from a recent TACOM briefing is shown in Figure 2. Comparable timelines were also shown in briefing packages and similar material from other TACOM projects.

From Figure 1, several user requirements can be extracted. First, the designer is aware of the advantage of incorporating vulnerability reduction concepts early in the concept formulation. Of course, guidance at this point must be quite generic, stressing the application of basic vulnerability reduction principles. Several offices asked about the possibility of developing an expert system type of program. Such a program would ask the questions and give the insights as an expert ("a Kirby" †) would do were he part of the concept formulation team. A more resource intensive response would be to have a vulnerability expert participating

†Mr. Robert Kirby, USABRL, established (experienced) expert in vulnerability analysis

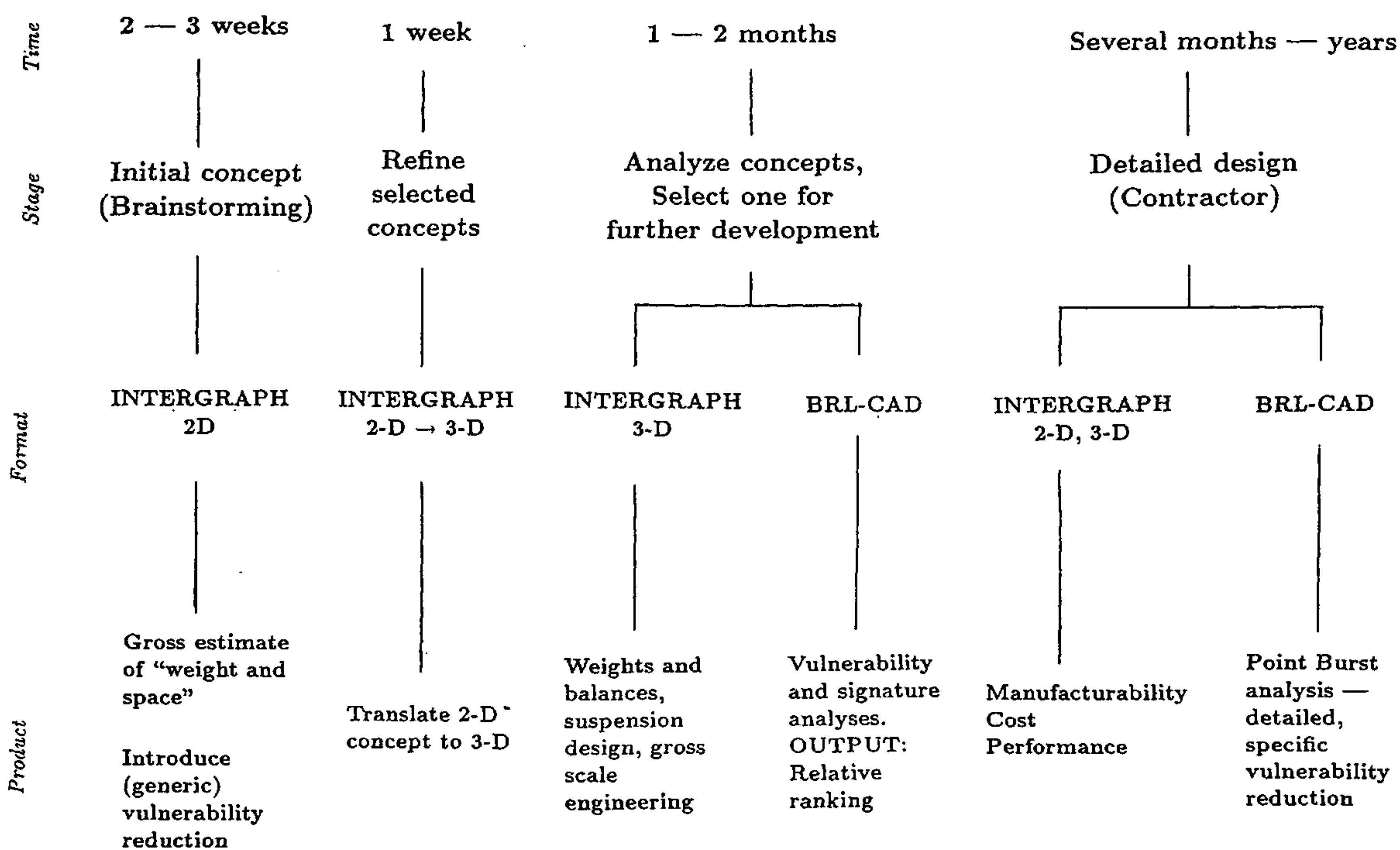

Figure 1: Typical Timeline for the Development of a Tank Concept

CONCEPTUAL DESIGN - ANALYSIS PROCESS

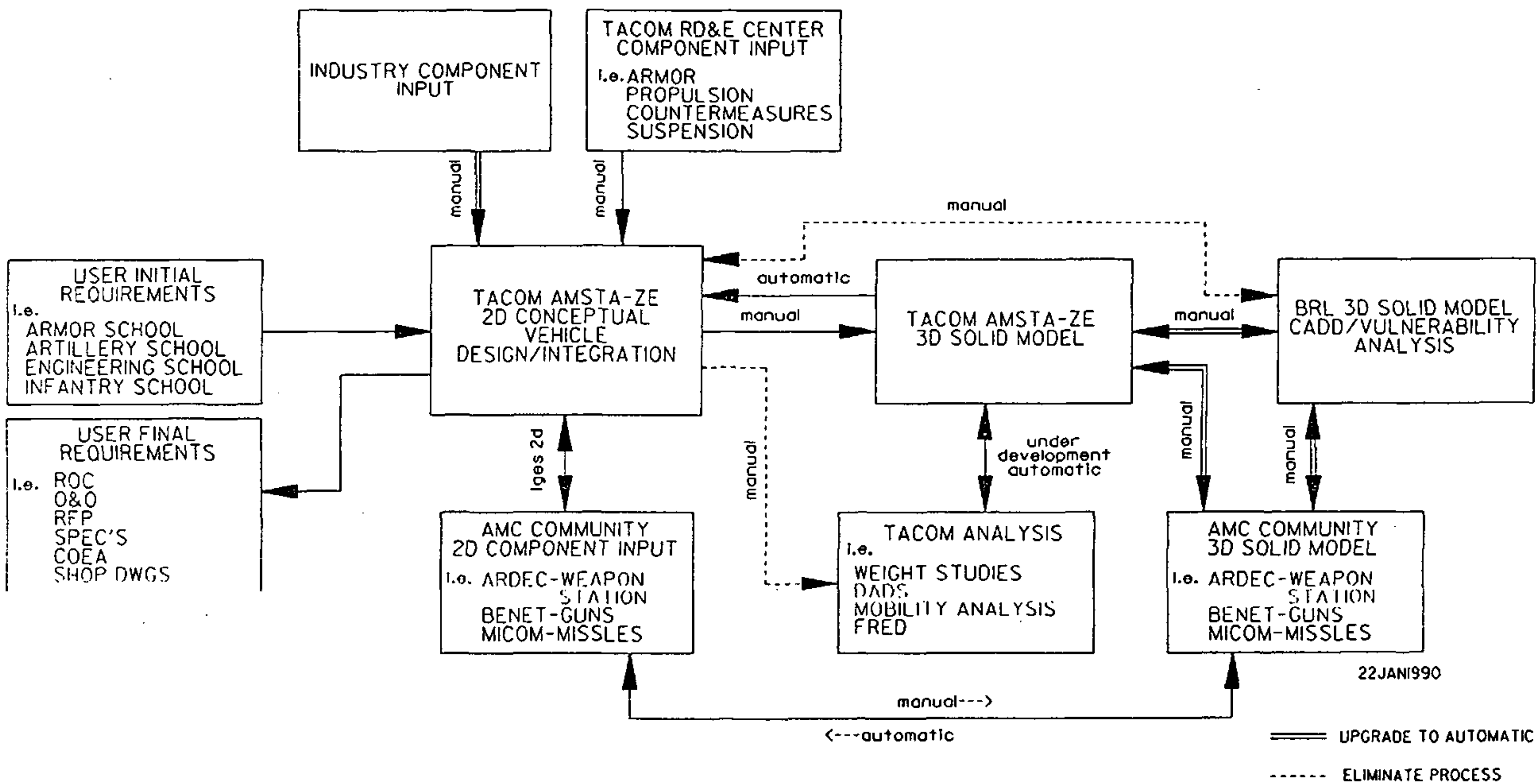

Figure 2: Conceptual Design - Analysis Process Flow-chart

on the concept formulation team. Unfortunately, this would require full-time vulnerability personnel, a concept that proved unsustainable in the VAT‡ project.

The next place at which vulnerability considerations enter into the concept process is in the first evaluation phase. At this point, the concept has been somewhat developed. In particular, for an armored vehicle, most of the armor package has been specified. (This is clearly necessary in order that the "weights and balances" analysis can be done.) Vulnerability analysis is needed at this point in order to select a candidate concept for further development; i.e., analyses need only determine that "A is better than B", rather than produce absolute numbers for A and B.

This lesser requirement is in keeping with the still low detail of the concept at this point. Recall that, while the major systems have been identified and "blocked-in", details such as wiring and hydraulic lines have not been considered. Thus, vulnerability analysis at the compartment level, with consistent estimates for the damage correlation curves, is both possible and appropriate.

2. Contractor

Following selection of a candidate concept, the initial concepting process is finished and the surviving candidate goes on to more detailed development. Often, this part of the process will be done by contractors. Therefore, an interview was held with analysts from two armored vehicle manufacturers. At the time of the interviews, one contractor (General Dynamics) was in production of a major weapon system (M-1 tank). The other (General Motors) has developed an extensive in-house capability in anticipation of contract bidding.

a. General Dynamics A requirement for BRL-CAD target descriptions has been included in RFPs for certain of developmental candidates. As a result, contractors are producing and using them in their analyses: In the company interviewed, this process begins at the beginning of the contractor's effort. In fact, the contractor had no complaints about this requirement. He stated that the company strongly favored vulnerability modeling and analysis from the beginning of their effort. Rather, the contractor's complaints came in two areas: the user-friendliness of the BRL-CAD and the state of the analysis codes.

‡Vulnerability Analysis Teams (located at various vulnerability user agencies) - a project carried out in the 1970s.

i. User-friendliness The first problem that arises in importing a new code — especially one that involves graphics — is the compatibility of the receiving machine. In the case of BRL-CAD, the compatibility issue extends to the operating system: the host machine must run UNIX. The contractor indicated a willingness to confine his work to UNIX machines, although that imposed a significant restriction on the facilities at his disposal. However, the graphics terminals which he must use are generally not the same as those used at the BRL. Therefore, drivers for his terminals — and maintenance for those drivers — are essential.

(N.B. The contractor, General Dynamics, is a very large, big budget operator. Other users may be more restricted than the one interviewed.)

The second need, also identified above, is for an automated means of transferring computerized descriptions between BRL-CAD and other CAD-CAM packages. In this case, the contractor uses Computervision's CAD-CAM package. It was pointed out that the translation is not just an exercise in computer-science and geometry. From a vulnerability analysis standpoint, the CAD-CAM description is far too detailed, containing a prohibitively large number of inconsequential components. Thus, some expert judgement must be involved in the translation. However, the contractor stressed that these difficulties by no means lessened the need for a technique — perhaps a hybrid of automatic, semi-automatic and manual steps — to quickly and reproducibly translate between CAD systems.

The third identified need was for a much improved capability to make changes in existing target descriptions. In this case, the application was to allow the user to incrementally build his product and analyze it as it develops. For example, it is common for the fire control system (FCS) to be under development while the turret and hull are being designed. Thus, for the first vulnerability analyses of the turret-hull, the FCS is represented by boxes of appropriate size and constitution. The importance of being able to easily substitute a model of the actual FCS when available was stressed. (This need will be further developed in the following sub-section.)

ii. Code maintenance The contractor's major complaints dealt with the state of the vulnerability analysis codes which use the BRL-CAD geometric models. Apparently, the contractor has found numerous errors and shortcomings in BRL-supplied codes such as VAMP, VAST and SLAVE. These shortcomings included such problems as inconsistent and incomplete penetration models, lack of fault trees (VAST) and outright coding errors.

The user also asked about the availability of SQuASH, stating that the common use of a state-of-the-art model might improve the level of model maintenance.

(Note: Although the user recognized the need to use a point-burst type model, the RFP to which he was responding called for a compartment model (VAMP) to be used in the analysis.)

b. General Motors Reflecting their current activities in the armored vehicle development and acquisition process, the individuals from General Motors concentrated most of their comments in the area of concept design and evaluation. In this area, recent experiences had uncovered several shortfalls in the evaluation process, some of which may, in part, be alleviated by methodological extensions.

i. Evaluation of conceptual vehicles The concerns of the interviewees fell into two broad classes. First, the simplified vulnerability analyses that are done (by the user-evaluator) discredit some good vulnerability practices. For example, many simple models automatically score a penetration into a fuel tank as a kill. However, redundant fuel tanks, placed outside of the armored compartment, can actually serve as a shield and a shaped-charge pre-initiator. Thus, such simple models may actually penalize good vulnerability practices. Since this happens early in the design process, many bold, new concepts will be suppressed before the more sophisticated evaluations can be applied — a suppression resulting not from shortfalls in the concepts but from the artificialities introduced by the simple evaluation tools employed.

The requested methodological fixes to this problem are:

- Expansion of the tools used, e.g. by TACOM, at the concept evaluation stage to credit good vulnerability practices.
- The insertion of stochastic factors into the simple tools. (Even the compartment model could incorporate the stochastic nature of penetration, e.g., resulting in significantly increased realism with little increase in labor.)

As a measure of the level of detail/complexity of models that are used at this stage of concept development, it was pointed out that analysts will always lag behind the designers. However, a response time of 3 – 4 days is sufficient to maintain the pace of a normal concept design process.

The second concern, one voiced by many individuals in competitive situations, deals with the disadvantage that an honest evaluator may face when making "subjective" choices. For example, in cases in which standard data is not available, analysts appear to be free to slant the surrogate data to best serve their own causes. Similarly, situations not covered by standard analysis tools (e.g. multiple hits on rugged components) can be interpreted in the analyst's best interests.

The fixes to this set of concerns are more procedural than methodological and are the responsibility of the evaluator (e.g., TACOM) rather than of the BRL. However, the BRL may be able to assist in the following ways:

- Keep a current standard library of penetration codes and associated data (e.g. efficiencies). This would allow the user (e.g., TACOM) to more precisely specify the analysis tools to be used on a project.
- Serve as an arbiter in evaluations, thus removing subjective decisions from those with vested interests.

ii. Methodological improvements The individuals at General Motors were unreserved in their praise for BRL-CAD, calling it "the best solid modeler available". In fact, after doing a design using a conventional engineering CAD package (ANVIL 5000), the designers will use a concurrent BRL-CAD model of the design to check for the fit of the various pieces. However, every one of the designers stressed that the BRL-CAD was a complement to their CAD tools, not a replacement. The extensive engineering features built into engineering CAD packages and intensively maintained by large software companies are extremely valuable and appreciated by design engineers. Therefore, the need for translators from engineering CAD packages to BRL-CAD immediately came up. The General Motors staff had developed, in-house, a translator from ANVIL to BRL-CAD. Although quite primitive (it only translates solids) and manpower-intensive, the tool saves significant time for the group and is considered a minor triumph.

The group also boasted of an in-house developed translator from BRL-CAD directly into a finite element representation of a target which bypassed the need to use PATRAN.

In the area of analysis models, it was pointed out that a number of models use similar inputs or have similar algorithms. However, current tools require the analyst to tie a series of runs together: for example, MGED – VDECK – GIFT/RIP. A standard library of routines and models which could be automatically tied together was seen as a significant time savings as well as an enhancement in the consistency and comparability of various analyses.

In a more theoretical sense, the meaning of some vulnerability measures was questioned. For example, the interpretation of $P_K = 0.5$ as a 50% probability of no function versus a constant 50% decrement in function was brought up.

Finally, the usefulness of a "survivability designers handbook" was expressed. Such a work could include, for example, live fire results and data as well as a compilation of good survivability practices. However, the interviewees stressed that the necessary simplicity of such a handbook made it prone to be strongly scenario-dependent. Furthermore, there might be a temptation for evaluators to use such a book as a "report card that take the place of actual vulnerability analysis", which would be a serious disservice to the production of survivabile vehicles.

iii. Procedural expansions The General Motors group also broached the subject of communication between government laboratories and industry. The importance of "Industry Days" was brought out. However, such open fora are inappropriate for the transmittal of specialized and, in particular, classified data. Although this observation lies outside of the scope of this report, it is worth noting that organizations — especially those involved in competitive design projects — may have a difficult time getting the data upon which to base decisions. This, in turn, limits the choices made available to the user-evaluator.

3. PM-AFAS

The observations of the AFV contractor were echoed, very independently, by the point of contact at PM-AFAS. In anticipation of the interview, the POC had assembled a list of needs/shortcomings. These included:

1. BRL-CAD is unique in commercial world and hard to learn.
   - Many CAD-CAMs currently in use. Forcing contractor to use BRL-CAD is very expensive.
   - Documentation for BRL-CAD was totally insufficient for users; must get education directly from the BRL
   - Succinct guidelines needed, especially for level of detail required, fault tree construction and similar qualitative decisions.
2. Do not have a generic "damage assessment" list; thus, are hindered in ability to conduct vulnerability analyses early in program. Need damage assessment lists from previous studies.

3. Need ability to do "what-if" drills. Given a model (from contractor), must be able to:
   - "Turn-off" components
   - Change material codes
   - Move simple components, add armor, etc.

   In the standard (45 day) time schedule for response to a contractor's proposal, the POC felt that **two weeks** might be allowed for doing "what-if"s.
4. Related to the need to relocate simple components: Need ability to do simple movements of movable components: e.g. rotate turret, elevate gun. (Difficulty with flexible components is acknowledged.)

The POC also discussed the need for someone — preferably the BRL as the Army's center of expertise for vulnerability — to verify the target description/analysis done by contractors. For example, if a contractor neglected to put a critical component into his description or into his fault tree, the contractor would be rewarded with a less vulnerable product.

4. Mature Systems

The requirements for vulnerability analysis of mature systems are not qualitatively different from those of a developmental system in the "what-if" stage. The POC at PM-Bradley was very complimentary about the BRL support in the area of vulnerability analysis in sharp contrast to the delays involved in contractual support. However, he did acknowledge that the response times would certainly be different if a highly detailed target description did not exist.

Vulnerability analysis in support of a mature system falls mainly into two classes: support of live-fire tests and conduct of "what-if" studies for PIPs. The former will be discussed below.

The conduct of "what-if" studies presents an opportunity to improve the BRL vulnerability tools. The typical "what-if" study involves making minor,but finite, physical changes to a vehicle: typical are addition of armor or the movement/interchange of a few components. The typical time budget, independently elucidated by several of those interviewed, was 1–2 weeks, allowing only a day or two to make any changes in the target description. To the uninitiated, this appears to be more than ample time. However, the interviewee pointed out that BRL-CAD was designed, built and optimized for the construction of new target descriptions. In the process, decisions may have been made to take advantage of the situation generally prevailing in the construction of a new description: For example, the describer tends to be familiar with the whole target, tends to plan ahead and tends to allocate space for all components in an area before modeling any of them. These conditions generally do not pertain when minor adjustments are being made to existing descriptions. Interactive tools are needed which would facilitate simple changes in a model from the viewpoint of an analyst unfamiliar with the details of the baseline description.

The importance of "what-if"s, upgrades and PIPs, other analyses that may involve modifications of old equipment was underlined by those interviewed in the TACOM Survivability Division. Those interviewed feel that Congress will be ever more unwilling to buy brand new equipment. Thus, redesign and upgrading of current materiel will become increasingly important.

5. Other considerations

Other points brought out in the interviews:

1. Vulnerability analysis cannot be limited to penetrating munitions. For example, the impact shock from a heavy, hypervelocity missile striking the turret of a tank might be enough to render the tank inoperable, even if penetration of the armor never occurred.
2. Almost all vulnerability analyses end up in comparisons. It is extremely important (and sometimes very difficult) to assure that the same measures of effectiveness are applied to all candidates. Similarly, studies done at different times are very apt to have different assumptions built into them. (For example, perceptions of foreign threats change over time.) It is important that the BRL (which has the final "imprimatur" on vulnerability data) is able to (re)generate large amounts of data at one time in order to guarantee identical assumptions.
3. Vulnerability analyses should be accompanied by confidence bounds. These should reflect — at least — the uncertainty in the input data. At best, uncertainties introduced by the methodology employed should be included. (For example, the uncertainties accompanying a compartment model run should reflect the assumptions made in using damage correlation curves.
4. The BRL role as "honest broker" is extremely important to the community.

6. Summary of Equipment Designers' Needs

a. Computer Methodologies In addition to those vulnerability/lethality tools currently in use, the equipment design community appears to have need for the following tools:

- Easy to use guidelines to aid the designer early in the design process. Several users mentioned the possibility of an "expert system" for the designers.
- Augmentation of simple models (fundamental compartment or follow-on models) to better credit good survivability practices and include stochastic factors)
- An interface between the engineering tools/computerized drawings and the BRL-CAD system.
- Automated, computer-efficient large batch-run capability (possibly at the BRL) to support Procedural Augmentation 2 below.

b. Time Budgets With the exception of generic guidelines to be used in the initial concept phases, there appears to be no justifiable need for one hour turn-around of vulnerability analyses. (Of course, "in the best of all worlds", an interactive capability would be of some use.)

On the other hand, several developers mentioned the need for one week turn-around of "what-if" level analyses.

Finally, for a brand-new concept, it appears that one month would be a suitable turn-around time, since other analyses (e.g. weight and balance) are proceeding simultaneously.

c. Procedural Augmentations The following procedural points were also brought out:

1. The VLD should be involved early in the design phase of an item. "Survivability people should be on the design team."
2. When providing data that a requester is going to use in a comparison of two items, or when competing agencies are producing items that are going to be compared, it is essential that:
   - MOEs be consistent
   - ALL factors be IDENTICAL, varying only those involved in the comparison.
   - Standardized evaluations methodologies and data be used by all parties for all items being compared.

These ends may be best met by (re-)running all data in one batch.

3. Confidence bounds should be published with all VLD output.
4. There must be constant, high-quality, responsive maintenance of the standard vulnerability codes.
5. The VLD must continue to be the honest broker of vulnerability data. Similarly, the VLD is often the best placed government agency to serve as arbiter for non-standard cases.
6. "Farming out" vulnerability analyses to contractors is costly in both money and credibility.

B. Warhead Design

1. PM-TMAS

In the warhead design community, only PM-TMAS was contacted; the point-of-contact was Mr. S. Rachlin.

Although (as expected) much of the warhead design community's BRL interaction is with the Terminal Ballistics Division, PM-TMAS has a substantial interaction with Ground Systems Branch. This evolves from the fact that warhead design involves factors other than pure penetration, for example, round-to-round dispersion.

The time line in the Warhead Design community is quite simple. As soon as someone comes up with an idea, the managers ask "How effective will it be?" Because of the interaction of parameters, the best answer to that question is lethality, not just penetrability.

A significant problem in returning an answer to a new concept is the complexity of the interaction of a warhead with the new active and passive armors. It is appreciated that no simple formulas or analytical techniques exist to predict the performance of a radically new projectile or shaped charge against the modern armors. Thus, the time is needed for the Terminal Ballistics Division (BRL) to produce its best-guess algorithms for penetration.

On the other hand, there is no need to update the target group for every new concept (as in vulnerability studies).

The *desired* turn-around time for a typical "what-if" request is 1/2 day; a *reasonable* turn-around time is 1/2 week. Here, a "what-if" request is defined as one that involves only a simple change in a warhead parameter (e.g. "What if the rod were 5 cm. longer? what if the striking velocity were 100 m/sec faster?") In the case of a more radical warhead change, the turn-around time would have to reflect the increased time needed to estimate the new concept's penetration capabilities against the various armor configurations. However, it would often be of significant value to the developer if conditional ("top-of-the-head") estimates of penetration performance could be run against a standard series of targets to indicate whether the warhead is even "in-the-ballpark".

As for accuracy, for simple "what-if" requests, data that would result in $\pm 5\%$ *in* $P_{K/shot}$ is great. Note that $P_{K/shot}$ involves grid cell data in a weighted average around all aspects of the target, as well as several other parameters: thus, the above accuracy requirement is less stringent than a requirement on the vulnerability data itself.

The time-requirements for new targets was quite loose. The POC pointed out that the warhead designer is almost always concerned about *future* foreign targets, rather than ones that are currently fielded. These targets are commonly based upon intelligence estimates of foreign technological progress, extrapolated out 5 to 20 years. Clearly, not much confidence can be placed in the specifics of an estimate actually becoming a reality. However, it is essential that the warhead designer have a yardstick by which to measure the performance of his product. Thus, the most important characteristics of the target description are not its specific features, but rather its ability to act as a standard for comparison that is applicable in the mid- to far-term. This translates into two basic requirements:

- The description is accepted as representative of the time-period.
- The description is stable.

The result is that, once a new target is "blessed" by DCSINT, the warhead developers would like to have the description brought up and used in analyses. However, to be a yardstick, it is essential that the new version be calibrated against its predecessor; i.e., all previous runs must be re-done. In particular, if a comparison is being made by anyone, it is essential that warhead A — fired against the new version of a target — be compared against warhead B, *fired against the same version.* Methodologically, this translates into a need for an automated means of re-running a complete set of analyses as a standard response for any data request.

The POC was very sympathetic to the work load at the BRL as well as the need to maintain the quality of the BRL products. However, he suggested procedural changes to improve the interaction between the BRL and the warhead designers. Primary among these is the need to establish a single point-of-contact to expedite a data request. The POC saw the BRL as being highly compartmented and pointed out that it was quite difficult for an outsider to, individually, make the necessary contacts within TBD and VLD in order to get a "what-if" analyzed. He also complained that the VLD would not accept weapon parameters (such as penetrator velocity) directly from him, implying that internal red-tape artificially extends his turn-around time.

2. Summary of Warhead Designer Requirements

The warhead designers do not appear to need any radically new methodologies. However, they do require the VLD standard methodologies (compartment and point-burst) to be amenable to quickly changing penetration equations/models to account for extended performance against complex armors. To implement a new penetration phenomenon or new standard future target, automation of batch-runs may be required.

The warhead designers would benefit from the procedural changes listed in c., above. In addition, the designation of a single expediter in BRL for vulnerability requests would greatly simplify the interface between the designer and the BRL.

C. Test Prediction/Postdiction

Although the author believes that the area of test prediction and the analysis of test results (postdiction) are important applications of vulnerability methods, he was unable to find an agency as deeply involved in the area as is the Ballistic Research Laboratory. It was therefore decided to include pertinent sections from BRL MR-MR-3755 (P. H. Deitz and A. Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing,* May 1989) to characterize the role of vulnerability analysis in this area. However, it was also desired to restrict the material in these sections to comments expressed by those outside of the BRL. Therefore, the included sections of BRL-MR-3755 have been placed in Appendix A.

D. Item-Level Performance

The Army's leading agency for item-level analyses is AMSAA. Accordingly, an interview was held with Mr. Will Brooks of the Ground Warfare Division (GWD) concerning the roles of and needs for vulnerability data at the item-level.

Although some use is made of item-level data directly, most of the vulnerability data sent to GWD is used to generate single shot kill probability (SSKP) data for larger studies. Examples of such studies are the Ammo Rates studies of the CAA and various COEAs. The role of AMSAA is to add the characteristics of weapon systems to the vulnerability data to produce SSKPs. As discussed below, the CAA requests generally do not require the generation of totally new data; rather, what is required is reprocessing of old targets, data, etc.

For a COEA, a new concept — requiring a new target description — may be involved. Ideally, this should not be a problem: 1) several months are generally scheduled for the data gathering portion of a COEA and 2) there is an good chance that a target description had been constructed during equipment development. As a result, responsiveness is generally not a big problem for this application.

The basic BRL supplied data consists of 4" cell data for PK and SSPK. For the latter, data is correlated into weighted sums by convoluting the cell data with standard (normal) dispersion distributions centered about standard aimpoints. AMSAA uses the 4" data to calculate SSKPs with biases, associates each data set with the applicable weapon-range-conditions and passes it on to higher level users.

In summary, the problems involved at the item-level are not different from those at other levels: in fact, during the interview, Mr. Brooks mentioned several problems and potential solutions discussed in other sections of this report. In particular, he referred to the problem of many concurrent studies competing for limited analytical resources. The main difference introduced at this level is the need for large sets of data since COEAs require large scale simulations which, in turn, involve many weapon-target pairs. For this reason, automation of the methodologies and procedures for selecting surrogates and rapid re-running of analyses promises benefits at this level.

E. SPARC

SPARC (Spare Parts And Repair for Combat) is a highly specialized application of vulnerability methodologies. In SPARC analyses, vulnerability studies are done that calculate probabilities of damage to specific components. Results for each shotline are tabulated by part name, number and repair time. As the name implies, SPARC analyses are part of the continuing process to maintain existing US combat vehicles and are therefore applicable to type-classified US systems and not to concept vehicles/systems.

As was the case with Test Prediction/Postdiction, the most experienced office in the subject area was in the BRL, in this case, the Logistical and Tactical Targets Branch (LTTB) of the Vulnerability/Lethality Division. However, since LTTB has little direct involvement in the development of the BRL methodologies being reviewed in this study, it was felt that the LTTB contribution to this document involved little conflict of interest. Therefore, for the sake of continuity, it was decided to leave the information on SPARC in place here, rather than relegating it to an appendix.

The level of detail required to model, simulate and account for thousands of components is extreme: recall that spare parts include such small but important components as wire bundles, gauges and manual controls. As a result, the demands of SPARC far out-weigh the demands customarily placed upon the vulnerability code (VAST or SQuASH) which has been adapted for SPARC use.

Typically, a SPARC analysis requires in excess of one man-year of effort. However, the bulk of this effort is in translating the information on each part — usually from cards ("aperture cards") which contain micro-filmed blue prints, one part per card — into a data entry for a ray-trace routine.

Two methodological improvements were discussed by LTTB. In short, there is need for an automated procedure to assist with the extraction of data from the aperture cards. (The author points out that some of this data might possibly be intercepted before it is printed out in "hard-copy" and microfilmed for the aperture cards, i.e. while still in the manufacturer's CAD/CAM format.)

A second methodological possibility brought up by the LTTB was that of developing relationships that would allow a counter-part to the compartment code methodologies for application to SPARC. In such a methodology, the exterior and major shielding components would be included in the target description. However, the probability of component loss would be estimated from such factors as residual penetrator and hole size, component presented area, location (compartment) and vulnerability parameters.

However, it was agreed by all that the methodological enhancements listed above were not general *vulnerability* methodology issues, per se, but were specific to the SPARC problem. It may happen, for example, that techniques adopted for the translation of the engineering tools/computerized drawings into the BRL-CAD system, discussed above, may have spin-off value here. However, it was concluded that the general vulnerability tools (ray-trace routines, penetration algorithms, etc.) which were directly applicable to SPARC analyses were quite adequate and introduced no new requirements for the purposes of this study.

F. Operational Planning

1. US Army Armor Center

The broad area of operational planning includes not only those studies needed to develop tactical concepts, but also those that focus upon the effects of new technology/equipment upon military operations. Inevitably, vulnerability/lethality data is required.

Operational planning for each mission area is generally the responsibility of the cognizant TRADOC school. Responsibility for the Close Combat - Heavy (CCH) mission area lies with the Directorate of Combat Developments at the Armor School at Fort Knox. In that school, all vulnerability data is channeled through Mr. Larry Vowels who was chosen as the expert/interviewee for this section.

Generally speaking, vulnerability data is not sent directly to Ft. Knox. Rather, data that is received and stored has been combined with firing accuracy data to produce probability of kill given a shot and given a hit ($P_{k/s}$ and $P_{k/h}$). Most commonly, the needed P_ks have been generated by AMSAA and either entered in the AMSAA "Series G" Handbook or sent to TRAC-WSMR, which is a regular data source for the Armor School. In those cases in which Mr. Vowels had to request vulnerability data directly, he was forced to generate the needed P_ks by hand, quite an arduous process.

Currency of vulnerability data is a greater concern than precision at the Armor School. This statement follows from the uses of vulnerability data. First of all, the usual intermediate outputs from analyses which go into an operational planning decision are at the force rather than system level. Therefore, fine details in the vulnerability data are lost in the averaging processes that are necessary to reduce the volume of data to an amount that can be handled in a force level analysis. Vulnerability data is combined with accuracy data and then averaged over all azimuths. Thus, the massive amount of data generated by the BRL for one round against one target is reduced to a few numbers that give probability of M, F or K kill at two or three ranges. (Force level models are discussed further in the subsequent section.)

Secondly, the decisions being made tend to be of a relative nature and only involve vulnerability/lethality factors indirectly. For example, a study of the benefits of a three-tank over a two-tank section will be dominated by increased opportunities versus increased cost. Given that the same vulnerability data is used for both the three and two-tank excursions, the precise tank-vs-target kill data will have little influence on the relative ranking of the two operational concepts.

On the other hand, insertion of an entirely new opposing tank (or an old one with enhanced armor) may make a qualitative difference in a study. In any case, use of outdated vulnerability/lethality data impugns the results. Thus, timely updating of the vulnerability database and efficient distribution of new data is an issue of importance with the Armor School.

As proponent for the CCH mission, the Directorate for Combat Development at Ft. Knox is involved in cost and operational effectiveness analyses (COEAs). Normally, the major COEAs are conducted by TRAC typically took one year from initial data gathering. This was an ample amount of time. In the case of the M1-A2 and Block 3 studies, although conducted in four months, the data lead time was acceptable since the ASM studies had already been in progress. However, serious time-problems did occur when the ASM re-runs were mandated. In general, Mr. Vowels appeared most understanding about the need for time to generate vulnerability data. ("...don't expect 10 day turn-around on a new concept") He stressed that "DA drives the train, makes decisions on new materiel concepts." In all, there were no complaints about the BRL timeliness in this area.

Similarly, there were no complaints about the completeness and comprehensiveness of the BRL/AMSAA data. Even for "what-if" studies (e.g. "What if the engagement opened at 4 km instead of 3?"), the desired insights can generally be gained by selecting ranges, etc. for which data already exists.

The major BRL/AMSAA shortcomings identified by Mr. Vowels dealt with the difficulties he has encountered in finding out what data does exist and getting access to that data. It is felt that AMSAA/BRL are — perhaps understandably — over-protective of vulnerability data. Ft. Knox' reliance upon TRAC-WSMR for data has come about largely because of the difficulty in getting data through AMSAA. A solution might be a catalog of data available, similar to the AMSAA "Series G" Handbook. Mr. Vowels went on to describe possible formats, contents, etc.

NOTE: Although BRL data is clearly involved, these comments pertained more directly to AMSAA than to BRL and will be pursued through other avenues.

The final concern that was voiced involved consistency within a database. This area is fraught with problems for the BRL. For example, a typical study might require comparing five different 105mm rounds against target X. Unfortunately, the BRL data — gathered for many sources — will have been generated over a several years and may have used several different methodologies and versions of target X. Often, the BRL gets blamed for the apparent inconsistencies. Mr. Vowels felt that the now defunct concept of "equivalent RHA" enhanced comparability, but realizes the inapplicability to new armors and designs.

2. Conclusions

Vulnerability data users in the area of operational planning are isolated from the BRL by intermediate levels of data manipulation, in particular the conversion of vulnerability data to $P_{k/h}$ and $P_{k/s}$. However, some of their currently unfulfilled needs, as expressed by Mr. Vowels, might impact indirectly upon the BRL. These include the need to produce consistent sets of data to support COEAs and comparison studies and the need to make more readily available catalogs of available data.

G. Force-level Models

Force-level simulations in the Army are primarily conducted by two agencies: the TRADOC Analysis Command (TRAC) for high and medium resolution (Battalion and Corps/Division level) and the Concepts Analysis Agency (CAA) for the low resolution (Theater level) studies. Within TRAC there are several agencies, most notably TRAC-WSMR (White Sands) with the nominal task of high resolution studies and TRAC-FTLV (Ft. Leavenworth) for medium resolution. However, a third agency, TRAC-RPD (Ft. Monroe) coordinates the external data collection for all TRAC agencies. While this arrangement adds consistency and comparability among studies done by various agencies, it also adds a time and management burden.

The centralization of TRAC data collection has resulted in an emphasis in recent years on the use of data which has been "certified" by an official of the generating agency. Interpretations of this requirement may place heavy burdens upon data generators. For example, vulnerability data for a particular future foreign tank may be available from a previous project and usable, with caveats, in a current study. However, if the onus is upon the AMC to certify that the data is the best obtainable, a re-run may be necessary to take advantage of the latest intelligence information. In response, the AMC has insisted upon having an early look at the plans for upcoming studies in order to schedule timely data generation and certification of the required data.

Generally, the time scheduled for a major study is in the order of a year. Of that time, several months are commonly spent in study management: planning the study, getting plan approvals, quantifying objectives, recruiting participants, etc. That leaves one to four months for data gathering.

In order to efficiently supply well correlated, certified vulnerability/lethality data , the AMC — the source of such data — identified the AMSAA as its single point of contact for studies data. The POC for such data is Mr. Don Blanton, who therefore represents all Force-level users. In turn, Mr. Blanton "farms out" the data requests to the BRL, TACOM, AMSAA, etc.

It is generally true that the responsibility for specifying required data lies with the study proponent. However, the AMSAA POC serves, unofficially, as a screen for requests, making sure that the proponent does not ask for vast amounts of unnecessary data/detail on a "just in case" basis.

Finally, as expected, there is an inverse relationship between the size of the study and the need for detail in the data. As a result, the broad use of surrogates is quite acceptable in theater-level studies, which require a huge number of weapon-target pairings (discussed below).

In addition to Mr. Blanton, POCs in CAA and TRADOC (Ft. Knox) were interviewed.

1. High Resolution: Battalion-level

Conventional weapon data for battalion-level simulations consist of weapon-target pairings. For direct fire weapons, such data include weapon characteristics and accuracy (from AMSAA) and "IUA" tables from the BRL. (IUA tables contain view-averaged P_K versus exposure, delivery error, attack angle and kill criteria.) For indirect fire weapons, BRL generally supplies vulnerable areas ($A_V s$) to AMSAA which uses them to calculate mean areas of effectiveness.

The typical time allotted for data gathering is 30 to 60, occasionally as much as 90, days. The number of weapons is limited — in the order of 10; similarly, the number of targets is in the 10s. However, very little production of new data will be justified by the time and money budget of a study. At most, old data may be tailored to fit new versions of old equipment, retrofits, etc. The primary exception may be the study item of interest: For example, in a simulation to evaluate the advantages of a new tank, that tank might be newly modeled in detail.

However, it must be noted that battalion-level models can involve a fair amount of detail. For example, such simulations often account specifically for the aspect angle between the firer and the target, rather than using a single view-averaged P_K. The benefit of this practice may be questionable if the data file itself was tailored from a surrogate by the subjective judgements of an expert.

Thus, the needs of the high-resolution model can be summarized as 100s of firer-target pairs for both direct and indirect fire weapons with full detailed output. The time frame for gathering/generating this data is 30–60 days.

2. Medium Resolution: Corps/Division-level

The difficulties encountered in the medium level resolution models fall between the High and Low resolution and will thus not be further discussed here.

3. Low Resolution: Theater-level

The Army's center of expertise in theater-level analysis is the Concepts Analysis Agency (CAA). POC for input data for CAA analyses is Mr. Greg Andreozzi.

In short, CAA looks to AMSAA for all its data. In the area of vulnerability/lethality, this data is generally in the form of single shot kill probabilities (SSKPs), lethal areas and weapon accuracies. In the past, requests for data have been generated for each study; however, a concerted effort is now underway to generate, in advance, requests for a year's worth of data. This procedure should help the supplying agencies (AMSAA-BRL) to anticipate and better schedule data production.

In fact, data sent to CAA is not directly used in theater-level simulations. Rather, it is necessary to run simulations at a lower (division) level and aggregate various division results into a theater analysis. The division model most often used for this process at the CAA is COSAGE. COSAGE itself is only resolved down to battalions. Thus, data on individual shots against individual targets (for example, single shot kill probability data) is highly aggregated before entering CAA analyses, several levels below the final outcome. Needless to say, details in the vulnerability data tend to get "washed out".

For this reason, it is generally acceptable to use surrogate weapons and targets in supplying AMSAA with data that will be sent to CAA. However, considering all the possible weapon-target-range pairings in a theater, it is clear that the volume of data in a request can be significant. The major methodological need, therefore, is for an efficient system of data retrieval and, in some cases, data generation using previously prepared targets and weapon characteristics files.

H. COEA, SSEB, Ad Hoc Studies

COEA, SSEB, Ad Hoc Studies were included in this report for the sake of completeness. In fact, analyses of this type generally involve a coordinated compilation of studies of the types discussed above (High-and Low-resolution force-level simulations, "what-if" studies, and so forth.) Since these have been discussed above, no further discussion is necessary here.

IV. Summary and Recommendations

This project was undertaken to establish the need for new vulnerability methodologies, particularly ones which would not fit into the current hierarchy of vulnerability models. The approach has been to interview users of vulnerability data at all levels from basic equipment design to high-level wargamers. Several dozen individuals representing AMC, TRADOC, CAA and their contractors were interviewed.

It is the conclusion of this study that no fundamental methodology gap exists: the models and methodologies extant in the vulnerability community span the range of needs and applications found.

However, the agencies interviewed did bring out several problems which might be alleviated by improvements in the existing information, in the capabilities of the methodologies in general and in the BRL operating procedures.

RECALL:

The purpose of this article is to report the results of interviews of users of BRL-CAD and BRL vulnerability/lethality models and data. The presence of items on the following list does *NOT* indicate a BRL conclusion that they are, in fact, true deficiences nor that addressing those that are deficiencies falls within the responsibility, capability or best interests of the BRL. On the other hand, in some cases, efforts are already underway at the BRL to alleviate some of the problems listed below. Discussion of these efforts is also beyond the scope of the present report.

The major shortcomings identified by the users were:

- **Lack of a useful guide to vulnerability practices.** Users feel that they could avoid vulnerability errors early in the development cycle if they had a guide, written with them as the intended audience. A (computer-resident) expert system was a suggested alternative. Also, the possibility of having a vulnerability expert "on the early design team" was another suggestion.
- **Need for extensions to current simple models to credit good survivability practices.** This shortfall was brought up by an agency which felt that evaluators, such as TACOM, may be inadvertantly suppressing new concepts because the simple evaluation

tools used early in the concept evaluation stage do not credit novel applications of good vulnerability reduction. Similarly, addition of stochastic factors into simple models may result in significantly more realistic outputs for little additional input.

- **Lack of translators between BRL-CAD and other CAD/CAM packages.** This shortfall came up often. Note that the program need not be totally automated, nor perfect and complete at the first unveiling. However, it must be very user-oriented. To succeed, such a package should be given the priority and investment of foresight, expertise and dedication that was given to BRL-CAD in the first place.

  As a related note, interviewees involved in engineering made it quite clear to the author that the design and engineering agencies that serve the US Army will not adopt BRL-CAD for basic engineering applications. Thus, the existence of translators which would make BRL-CAD an accepted adjunct to a firmly-entrenched engineering methodology is definitely in the interest of BRL-CAD.

- **Need for a comprehensive, automated data renewal/data retrieval system.** By *renewal* is meant a means of re-doing large numbers of calculations to reflect changes in parameters. This is the only means that the author could propose to solve the problems of data inconsistencies which were the most prevalent concern at all levels. Ideally, for every major study, the study team could come to its data source (ultimately, the BRL) and get a complete package of all the vulnerability data to be used, freshly generated for that study. With the facilities available to the BRL, this may be a realizable goal.

- **Need for a formal, automated and defendable procedure for selecting surrogates.** The goal is to reduce the subjectivity that currently surrounds the data sent for use in large simulations. While the subjectivity may never be wholly removed, the use of a formal, automated procedure offers a reasonable guarantee of consistency and removes the apparent opportunity for injected biases.

- **Need for significant enhancement of user-friendly features.** In spite of the remarkable success that has been enjoyed in the spread of BRL-CAD, many users do not consider it easy to use. Documentation is felt to be very obscure and unfriendly. As a result, several users expressed interest in user-oriented enhancements.

- **More emphasis on methodology maintenance.** In particular, the older codes that still play an important role in vulnerability studies (e.g. VAST) must be maintained or replaced. It is understood that MUVES will satisfy all the methodological needs of the vulnerability community and that older models will be allowed to deteriorate. However,

- MUVES is not now in full production mode, and
- even when MUVES is completed, it must be transitioned into the community over a extended period of time during which current old methodologies will still be in use.

The conclusion is that rudimentary maintenance of the old methodologies, unpleasant and unfulfilling as it may seem, must be done until MUVES is in place and running in a significant number of the influential agencies. **Since such models were released by the BRL without promise of maintenance, it is not clear that the BRL has a responsibility to provide such.** However, the BRL should

1. expedite the development, testing and distribution of a new-generation standard suite of methodologies, for which the BRL will assume responsibility, and
2. provide reasonable assistance to users of old BRL methodologies until the BRL is prepared to universally distribute replacements.

In addition, four specialized requests were received.

- TACOM would like to be able to rotate the turret on an existing target description. This would require some significant ingenuity in designing geometrical constructs that can stretch and change shape in order to model wire bundles, etc., that have both stationary and rotating portions.
- A number of agencies asked about the possibility of generating confidence bounds along with vulnerability estimates. Although this information would have little direct applicability for the large-scale, low-resolution users, it would be of use in the interpretation of results for the detailed studies.
- The BRL is often sought to serve as the "honest broker". One manifestation of the role is the keeping of standard libraries of parameters, such as penetration efficiencies. Another is acting as an arbiter in non-standard cases. In fact, the BRL often provides such services while serving on source selection boards and providing similar services to TACOM, TRADOC, etc. Therefore, this request can be taken as a formal recognition of the importance of such service.

- Finally, the BRL was asked to assist AMSAA should it be convinced to develop a catalog of available vulnerability data. Data requesters indicated that they would tailor their requests to take advantage of available data — especially if the requester would gain quicker response to his requests. However, the requesters generally do not know what data is available for fast delivery.

At the risk of setting up yet another bureaucracy, it was suggested that the VLD might profit from establishing a single point-of-contact, a few person office that would function as a "factory expediter, inventory controller and shipping department". Such an office would also be in a position to keep track of what analyses are in progress, thus helping to avoid the wasted duplication of effort that can result from independent requests to different branches.

In summary, the users of VLD data are generally satisfied with the methodologies employed. Requested improvements lie mostly in the operating procedures and the available user-oriented facilities.

Finally, repeating the major conclusion stated above:

> **It is the conclusion of this study that no fundamental methodology gap exists: the models and methodologies extant in the vulnerability community span the range of needs and applications found.**

Appendix A

Test Prediction/Postdiction

1. Introduction

The Vulnerability Methodology Branch (VMB) of the BRL has been one of the most active DoD agencies in the area of live-fire prediction/postdiction, both in the development of statistically sound techniques and in the application of these techniques to extensive, high-visibility tests. In particular, the VMB developed the SQuASH (Stochastic Quantitative Analysis of System Hierarchies) Methodology in which precise hit point, warhead performance, residual penetrator deflection, spall production and component $P_{K/H}$ are stochastically varied. Through this technique, the methodology is able to predict probabilistic distributions of results — the only appropriate metric for a process as unpredictable as a live-fire vulnerability test.

In a recent report [3], Deitz and Ozolins listed their observations on model calibration and the live-fire objectives. These are reproduced in the following subsection.

2. Observations from BRL-MR-3755

a. Model Calibration Given the complexity of the vulnerability process revealed at this level of detail, it is anticipated that model calibration may prove exceedingly difficult. Particularly because many of the inputs to the model (i.e. penetration, BAD and component-damage algorithms) are poorly known. For the modelers at BRL, one of the key issues in the next phase of analysis is to compare the code predictions with the single outcomes of the field tests. Of great importance is to find what possible damage mechanisms may be evidenced that are not handled in the current code realization.

A related issue is the "validation"[†] of vulnerability models. There have been attempts to apply statistical tests to compare Live Fire LOFs with model predictions in order to judge the goodness of agreement.[4] [5] This

[3]P. H. Deitz and A. Ozolins, *Computer simulations of the Abrams Live-Fire Field Testing,* BRL Report BRL-MR-3755, May 1989

[†]Validation is a word that should surely be struck from the DoD lexicon. For more than a century, researchers have recognized that experiments don't prove theory, they can only *disprove* it.

[4]Paul H. Deitz, Jill H. Smith and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned,* Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium, 11-12 October, 1989, Ft. Lee, VA; also, Ballistic Research Laboratory Memorandum Report BRL-MR-3814, March 1990

[5]Paul H. Deitz, Michael W. Starks, Jill H. Smith and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment,* Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium, 10-11 October, 1990, Ft. Lee, VA;

has been problematic for a number of reasons; first, as we have seen above, the LOF metrics are non-parametric (although that fact wasn't known until this work). Thus any method which depends on outcomes being Gaussian distributed is inapplicable. Second, it is clearly impractical to derive LOF probability density functions from field tests, and until now, no model was capable of producing an estimate.

b. Penetration & BAD Data Emphasized throughout this paper has been the need for reliable data describing the overmatch phenomena for warhead/armor interactions. Full-up live-fire events are not the place to gather this data since they do not provide calibrated diagnostic media to capture such data. Further, since the most central phenomena in the vulnerability process are themselves often known poorly, it becomes all the more difficult in the post-test assessment to separate out the primary damage phenomenologies from those that are secondary.

c. Limitations of Component PKs The basic element for assessing component dysfunction is through component PK characterization. Much "off-line" testing of specific systems needs to be accomplished to generate an adequate data base. Even if the interaction of *single* fragments with components becomes better understood, the problem of *multiple* fragments must be put on a firmer foundation.

d. Secondary Kill Phenomena As noted earlier, it is anticipated that the analysis of the Abrams LF test data will provide valuable insight into the importance of this class of damage mechanisms.

e. Damage Synergism If and as other damage mechanisms are recognized to be important in this context and can be modeled, a further significant issue will then arise. Just as the multiple-fragment interaction with a single component is modeled in an unsatisfactory fashion, there are no extant algorithms for aggregating damage to a single component from *multiple* phenomenologies. For example if it were possible to model both shock and fragment interaction *individually* with a given component, there is no known method for combining the individual kill assessments.

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also, Ballistic Research Laboratory Memorandum Report BRL-MR-3814, In Press.

f. Aggregation of Loss-of-Component Effects As noted above, deactivation diagrams are the means by which individual component loss is aggregated up to the major system or sub-system level. This artifice needs to be examined more thoroughly both to learn whether this procedure is reliable in general and further whether the intrinsic subjectivity of the process when applied to a particular system leads to inappropriate biases.

g. System Damage to MOEs The historical method for accomplishing this task is *via* the Standard Damage Assessment List. This process is in dire need of replacement, and work to define alternative approaches is ongoing. Taking this procedure as a given, however, it is clear that typical system damage is very complex, and PK histograms ill-behaved. *Certainly comparing a single test PK with the first moment of the associated probability density function is useless. Even showing that the field PK is coincident with a single PK in the predicted PK histogram is irrelevant because entirely different damage states can map to the same point in PK outcome space.*

h. "Objective" (Field-Based) PKs From Section IV, the steps involved in deriving final PK values, whether from actual field shots or computer simulations, should be clear. A particular field shot corresponds to a single mapping from Space 1] to Space 2] {This refers to a figure in the original document. Spaces 1 through 4 refer to:

1. Warhead/Target Interaction
2. Component Damage State(s)
3. Measures of Performance
4. Measures of Effectiveness

That same mapping, or transformation process, is simulated in the SQuASH code. However, it is critical to note that *the step from Space 2] to Space 4], where the final PK or LOF value is derived, follows the identical transformation process whether the damage state is "real" or computer simulated.* Although it may be argued that the assessment of post-shot damage (in Space 2]) is an objective process, the criticality analysis[6]

[6] J. J. Ploskonka, T. M. Muehl, C. J. Dively, "Criticality Analysis of the M1A1 Tank", Ballistic Research Laboratory Memorandum Report BRL-MR-3671, June 1988.

and SDAL artifice[7] [8]

at the heart of the Space 2] to Space 4] mapping are highly subjective in nature. Thus even field data must undergo this somewhat arbitrary transformation. Further, *if meaningful comparisons of field data and simulations are to be made, then the identical mapping process must be used for both sets of data.* There have been instances in which field assessors have examined a vehicle following a live-fire test, made certain subjective conclusions about the level of damage, and then *intuited* a "PK" without regard to either the precise logic of the criticality analysis or the SDAL process. Clearly if this approach were to be utilized, there would be no hope of rationalizing field measurements with predictions.

i. Value of Full-Up Testing It is clear that even if all possible off-line tests were performed, the phenomena understood, and the related data bases established, there are other significant effects that can only be tested in a full-up configuration. Included in this category are blast and shock phenomena and ricochet, for example.

However from the modeler's perspective, the order of Live-Fire testing was initiated in a backward order. For example, the BRL has had to make preshot predictions for the Abrams program before any fragment/component firings have taken place. Although the test plan should be formulated in a top down fashion, the implementation should occur in a bottom up sequence. This is distinctly not the actual order of events.

j. Live-Fire Testing The Live-Fire program, not only for the Abrams but other military vehicles, will unquestionably improve the quantity and quality of data with which modelers can make more reliable assessments. However from the complexities of the vulnerability process evident even now with the new class of stochastic modeling *via* the SQuASH model, it is clear that statistical limitations will preclude any kind of rigorous validation. The best that can be expected will be that some uncertainties in the process will be subject to quantitative assessment.

[7] G.A. Zeller, "Update of the Standard Damage Assessment List (SDAL) for Tanks", Executive Summary, ASI Systems International Report 87-14, October 1987.

[8] G. A. Zeller and B. F. Armendt, "Update of the Standard Damage Assessment List for Tanks: Underlying Philosophy and Final Results", Submunition Evaluation Program, Project Chicken Little, Report AD-TR-65, November 1987.

3. Summary

From the above observations and private discussions, it appears that the major remaining methodological shortcomings are not in the overall vulnerability model (SQuASH), but with the data and algorithms that are embodied in the model. As discussed above, these include:

- Penetration and BAD data
- Component P_K
- "Secondary" Kill Phenomena
- Damage Synergism
- Aggregation of Loss-of-Component Effects
- Relating System Damage to Mission Degradation

In addition, it is important to question the fundamental assumption that the defeat of a target can be expressed in terms of the defeat of individual components. Tests to date have tended to confirm this assumption. However, indirect effects from individual components (e.g. a fire from a non-critical component which damages a critical one) must be artificially injected. At present, there is no general methodology to predict indirect effects: such effects are included in an analysis, through expert judgement, by assigning "false criticality" to the potentially dangerous component.

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